

Robust Adaptive Data Encoding and Restoration NCC-1-258

**Summary of Research
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This is the final report for NASA cooperative agreement NCC-1-258 and covers the period from 01 October, 1997 to 11 April, 2000. Enclosed are copies of the research products for which the research was supported by the grant, at least partially.

The research during this period was performed in three primary, but related, areas.

1. Evaluation of integrated information adaptive imaging.
2. Improvements in memory utilization and performance of the multiscale retinex with color restoration (MSRCR).
3. Commencement of a theoretical study to evaluate the non-linear retinex image enhancement technique.

The research resulted in several publications, and an intellectual property disclosure to the NASA patent council in May, 1999. The publications are listed chronologically in each category.

1 Information Adaptive Imaging

1. We have previously published extensively on the information theoretic assessment of imaging systems. In this paper, this concept is extended to include the effects of the display device, and the interactions with the human observer.

F. O. Huck, C. L. Fales, R. Alter-Gartenberg, S. K. Park and Z. Rahman, "Information-theoretic assessment of sampled imaging systems," Optical Engineering, Vol. 38, No. 5, pp. 742-762, (May 1999).

Abstract: By rigorously extending modern communication theory to the assessment of sampled imaging systems, we develop the formulations that are required to optimize the performance of these systems within the critical constraints of image gathering, data transmission, and image display. The goal of this optimization is to produce images with the best possible visual quality for the wide range of statistical properties of the radiance field of natural scenes that one normally encounters. Extensive computational results are presented to assess the performance of sampled imaging systems in terms of information rate, theoretical minimum data rate, and fidelity. Comparisons of this assessment with perceptual and measurable performance demonstrate that (1) the information rate that a sampled imaging system conveys from the captured radiance field to the observer is closely correlated with the fidelity, sharpness and clarity with which the observed images can be restored, and (2) the associated theoretical minimum data rate is closely correlated with the lowest data rate with which the acquired signal can be encoded for efficient transmission.

2. The concept of end-to-end imaging and its assessment is well described in the literature. However, simulations required to reproduce the reported results can be difficult to design without a proper understanding of the representations of the functions in the spatial and spatial frequency domain. This paper lays out in detail these various relationships and how

they can be used to properly simulate a sampled imaging system, and, hence, analyze its performance.

S. K. Park and Z. Rahman, "Fidelity analysis of sampled imaging systems," Optical Engineering, Vol. 38, No. 5, pp. 786–800, (May 1999).

Abstract: Many modeling, simulation and performance analysis studies of sampled imaging systems are inherently incomplete because they are conditioned on a discrete-input, discrete-output model that only accounts for blurring during image acquisition and additive noise. For those sampled imaging systems where the effects of digital image acquisition, digital filtering and reconstruction are significant, the modeling, simulation and performance analysis should be based on a more comprehensive continuous-input, discrete-processing, continuous-output end-to-end model. This more comprehensive model should properly account for the low-pass filtering effects of image acquisition prior to sampling, the potentially important noise-like effects of the aliasing caused by sampling, additive noise due to device electronics and quantization, the generally high-pass filtering effects of digital processing, and the low-pass filtering effects of image reconstruction. Yet this model should not be so complex as to preclude significant mathematical analysis, particularly the mean-square (fidelity) type of analysis so common in linear system theory. In this paper we demonstrate that, although the mathematics of such a model is more complex, the increase in complexity is not so great so as to prevent a complete fidelity-metric analysis at both the component level *and* at the end-to-end system level. That is, computable mean-square-based fidelity metrics are developed by which both component-level and system-level performance can be quantified. In addition, we demonstrate that system performance can be assessed qualitatively by visualizing the output image as the sum of three component images, each of which relates to a corresponding fidelity metric. The *cascaded*, or filtered, component accounts for the end-to-end system filtering of image acquisition, digital processing, and image reconstruction; the *random noise* component accounts for additive random noise, modulated by digital processing and image reconstruction filtering; and, the *aliased noise* component accounts for the frequency folding effect of sampling, modulated by digital processing and image reconstruction filtering.

2 Performance and improvements in the MSRCR

1. One of the tasks under the cooperative agreement NCC-1-258 was to improve the performance of the MSRCR on low-end computers. This task was accomplished by a complete redesign of the software implementation to allow it to run more efficiently on low-end machines. The processing times were reduced from several hours on a machine with 128MB of RAM to under an hour. In a similar vein, optimizations in the processing structure resulted in approximately three-fold speedups where the memory bottleneck was not an issue.
2. Related to the improvement in performance were some changes in the actual algorithm. These changes were subject of an intellectual property disclosure in May, 1999. The disclosure was

jointly filed at the NASA Langley Research Center and the College of William & Mary. The relevant document numbers are respectively: LAR 16011-1-CU and WM-003-99.

Invention—Improvements to the Multi-Scale Retinex with Color Restoration.

Two innovations have been developed that significantly improve the visual performance of the Multi-Scale Retinex with Color Restoration (MSRCR). By generalizing further on the original algorithm, optimal solutions have been obtained that encompass the widest possible range of input imagery. The MSRCR is the subject of a previous patent, US Patent #5,991,456 granted on November 23, 1999, and numerous publications[1]-[9]. While the MSRCR performs very well on diverse digital imagery as a general purpose enhancement method, we have developed two new methods that further extend and improve the original MSRCR. These are

- (a) automatic classification of the dynamic range of the incoming image and appropriate optimized adjustments in the post-retinex gain and offset, and,
 - (b) a post-retinex method for extending the performance for images with large white zones. This is especially important in document imaging where white pages with embedded color images in addition to the usual text are the norm.
3. The MSRCR provides the best results when the input image has not been modified in any way before processing. However, this cannot be guaranteed for a generally used process. In a 1998 conference paper, we investigated how pre-processing affects the final output from the MSRCR.

Z. Rahman, D. J. Jobson, and G. A. Woodell, "Resiliency of the Multiscale Retinex Image Enhancement Algorithm," Proceedings of the IS&T Sixth Color Imaging conference: Color Science, Systems, and Applications, Scottsdale, AZ, (1998).

Abstract: The multiscale retinex with color restoration (MSRCR) continues to prove itself in extensive testing to be a very versatile automatic image enhancement algorithm that simultaneously provides dynamic range compression, color constancy, and color rendition. However, issues remain with regard to the resiliency of the MSRCR to different image sources and arbitrary image manipulations which may have been applied prior to retinex processing. In this paper we define these areas of concern, provide experimental results, and, examine the effects of commonly occurring image manipulations on retinex performance. In virtually all cases the MSRCR is highly resilient to the effects of both the image-source variations and commonly encountered prior image-processing. Significant artifacts are primarily observed for the case of selective color channel clipping in large dark zones in an image. These issues are of concern in the processing of digital image archives and other applications where there is neither control over the image acquisition process, nor knowledge about any processing done on the data beforehand.

4. In addition to the improvements in performance, we extended the use of the MSRCR to classification of remotely sensed images. The idea was that since the MSRCR performs dynamic range compression and color constancy, it could be used to ameliorate the effects of

the atmosphere on the remotely-sensed image resulting in more consistent classification. We investigated this idea in two conference publications:

- (a) *B. Thompson, Z. Rahman, and S. K. Park, "Retinex Preprocessing for Improved Multi-spectral Image Classification," SPIE International AeroSense Symposium, Visual Information Processing VIII, (April 1999).*

Abstract: The goal of multi-image classification is to identify and label "similar regions" within a scene. The ability to correctly classify a multi-image of the scene is affected by the ability of the classification process to adequately compensate for the effects of atmospheric variations and sensor anomalies. More reliable classification may be obtained if the multi-image is pre-processed before classification, so as to reduce the adverse effects of image formation. In this paper, we discuss the overall impact on multi-spectral image classification when the Retinex image enhancement algorithm is used to pre-process multi-spectral image data. The retinex is a multi-purpose image enhancement algorithm that performs dynamic range compression, reduces the dependence on lighting conditions, and generally enhances apparent spatial resolution. The retinex has been successfully applied to the enhancement of many different types of grayscale and color images. We show in this paper that retinex pre-processing improves the spatial structure of multi-spectral images and thus enables better within-class variations than would otherwise be obtained with the original images. We show for a series of multi-spectral images obtained with diffuse and direct lighting that the class spectral signatures vary substantially with the lighting conditions without retinex pre-processing. Whereas multi-dimensional clustering without pre-processing produced one-class homogeneous regions, the classification on the pre-processed data produced multi-class non-homogeneous clusters. This lack of homogeneity is easily explained by the different nitrogen and water concentrations in the clusters: the pre-processed being closer to ground truth. The principle advantage that the retinex offers is that the classifications from the retinex pre-processed images for different lighting conditions look remarkably "similar", and thus more consistent, whereas classifications from the original images, without pre-processing, are much less similar.

- (b) *B. Thompson, Z. Rahman, and S. K. Park, "A multiscale retinex for improved multispectral image classification," SPIE International AeroSense Symposium, Visual Information Processing IX, (April 2000).*

Abstract: Image preprocessing is useful in helping to identify "spectral response patterns" for certain types of image classification problems. The common artifacts in remotely sensed images are caused by the blurring due to the optics of the image gathering device, illumination variations, and the radiative transfer of the atmosphere. The Multi-Scale Retinex (MSR) image enhancement algorithm that provides dynamic range compression, reduced dependence on lighting conditions, and improved (perceived) spatial resolution has proven to be an effective tool in the correction of image degradations such as those in remote sensing images. In this paper, we measure the improvement

in classification accuracy due to the application of the MSR algorithm. We use simulated images generated with different scene irradiance and with known ground truth data. The simulation results show that, despite the degree of image degradation due to changes in atmospheric irradiance, classification error can be substantially reduced by preprocessing the image data with the MSR. Furthermore we show that, similar to the results achieved in previous work, the classification results obtained from the MSR preprocessed images for various scene irradiance are more similar to each other than are the classification results for the original unprocessed images. This is evident in the observed visual quality of the MSR enhanced images even before classification is performed, and in the difference images obtained by comparing image data under different irradiance conditions. We conclude that the application of the MSR algorithm results in improved visual quality and increased spatial variation of multispectral images that is also optimal for certain types of multispectral image classification.

3 Theoretical assessment of non-linear retinex image enhancement

The work we have cited above is experimental in both development and in assessment. In order to develop a qualitative understanding of the algorithm, we have been working on an information theoretic assessment of the non-linear retinex-like processes. A brief description of the work follows:

- *N. Halyo, Z. Rahman and S. K. Park, "Information content in non-linearly processed digital images," under preparation.*

Introduction: Digital images, whether obtained by electro-optical or by purely optical instrumentation, provide information about the scene that they depict. The amount of information (about the original scene) contained in the processed image is a quantity of interest in the design of the image-gathering instrumentation as well as in the development of digital processing algorithms. The rate at which the information in the scene is transferred to the processed digital image is a good indicator of the efficiency of the image gathering system and the processing performed.

The information rate has been studied so far only for the special case of signals with Gaussian (Normal) power spectral densities (PSDs) in linear image-gathering and either linear[10, 11, 12] or linearized[13] digital processing systems. In this paper, we will investigate the rate of information transferred from the scene to the digital image for systems using non-linear processing and containing signals which do not necessarily have Gaussian PSDs. In particular, we will investigate the effects of Retinex and Local Normalization (LN) processing. While a closed form solution has been available for linearly processed Gaussian signals[14, 15], this solution is not valid when either the signals have non-Gaussian characteristics or when the processing involved is non-linear. We will investigate and develop an analytical form for the information rate for a specified class of non-Gaussian signals and for the Retinex and LN

processing.

Human perception of images depends more on the local characteristics of the image rather than the absolute magnitude of the image signals. Thus, the “eye-brain” or “retina-cortex” (retinex) system perceives image characteristics relative to the local (spatially weighted) average conditions. For example, the same gray level value will *appear* brighter when it is in a dark neighborhood than when it is in a bright neighborhood.

The main concept in LN processing is to obtain a weighted average of the digital image in a local neighborhood around each pixel and normalize that pixel value relative to this weighted average. Accordingly, the same gray level value will now be “brighter” if it is located in a shadow, i.e. low local average, and will be “darker” if it is located in a bright area, i.e. high local average.* In addition, in order to obtain the information rate with LN processing we concentrate on that portion of the image signal that describes the detail or high spatial-frequency information, instead of analyzing that part of the signal which is often due to variations on scene illumination rather than actual scene characteristics.

In considering the LN processing it is of interest to know how the rate of information varies with the application of the non-linear processing. Is the rate of information between the scene and the final digital image unchanged (or higher or lower) if the LN process is used instead of the well-known linear processes that are traditionally used? Is there an effect on the information rate if non-Gaussian scene characteristics are used as opposed to the traditional Gaussian PSDs? Whereas in previous studies we have assumed that the radiance signal is Gaussian in order to use the well-known results for the rate of information, it is clear that the radiance cannot have negative values and therefore cannot be Gaussian for that reason and possibly others. While the Gaussian assumption might well be an adequate approximation, it is of interest to find out if that is indeed so. Of course, we would like to obtain a relatively simple formula for the rate of information which can then be used to perform quantitative analysis similar to those done for the traditional Gaussian case. In the next sections, we will investigate and answer all the questions posed above and develop a new formula for computing the rate of information for LN processing of a class of signals that is not restricted to Gaussian. We will also investigate the impact of the various system parameters, such as those used to describe the image-gathering device, on the rate of information.

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*This is similar to the effect produced by retinex processing[4, 2].

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Information-theoretic assessment of sampled imaging systems

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